

US011167986B2

(12) **United States Patent**
Smith et al.

(10) **Patent No.:** **US 11,167,986 B2**
(45) **Date of Patent:** **Nov. 9, 2021**

(54) **BORON NITRIDE NANOTUBE SYNTHESIS VIA DIRECT INDUCTION**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **17/137,040**

(22) Filed: **Dec. 29, 2020**

(65) **Prior Publication Data**

US 2021/0139329 A1 May 13, 2021

Related U.S. Application Data

(63) Continuation of application No. 16/561,091, filed on Sep. 5, 2019, now Pat. No. 10,906,810, which is a (Continued)

(51) **Int. Cl.**

C01B 21/064 (2006.01)

B01J 10/00 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC **C01B 21/0641** (2013.01); **B01J 10/005** (2013.01); **B01J 19/0013** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC H04W 4/00; H04W 4/02; H04W 4/021; H04W 48/00; H04W 48/16; H04W 72/00;

(Continued)

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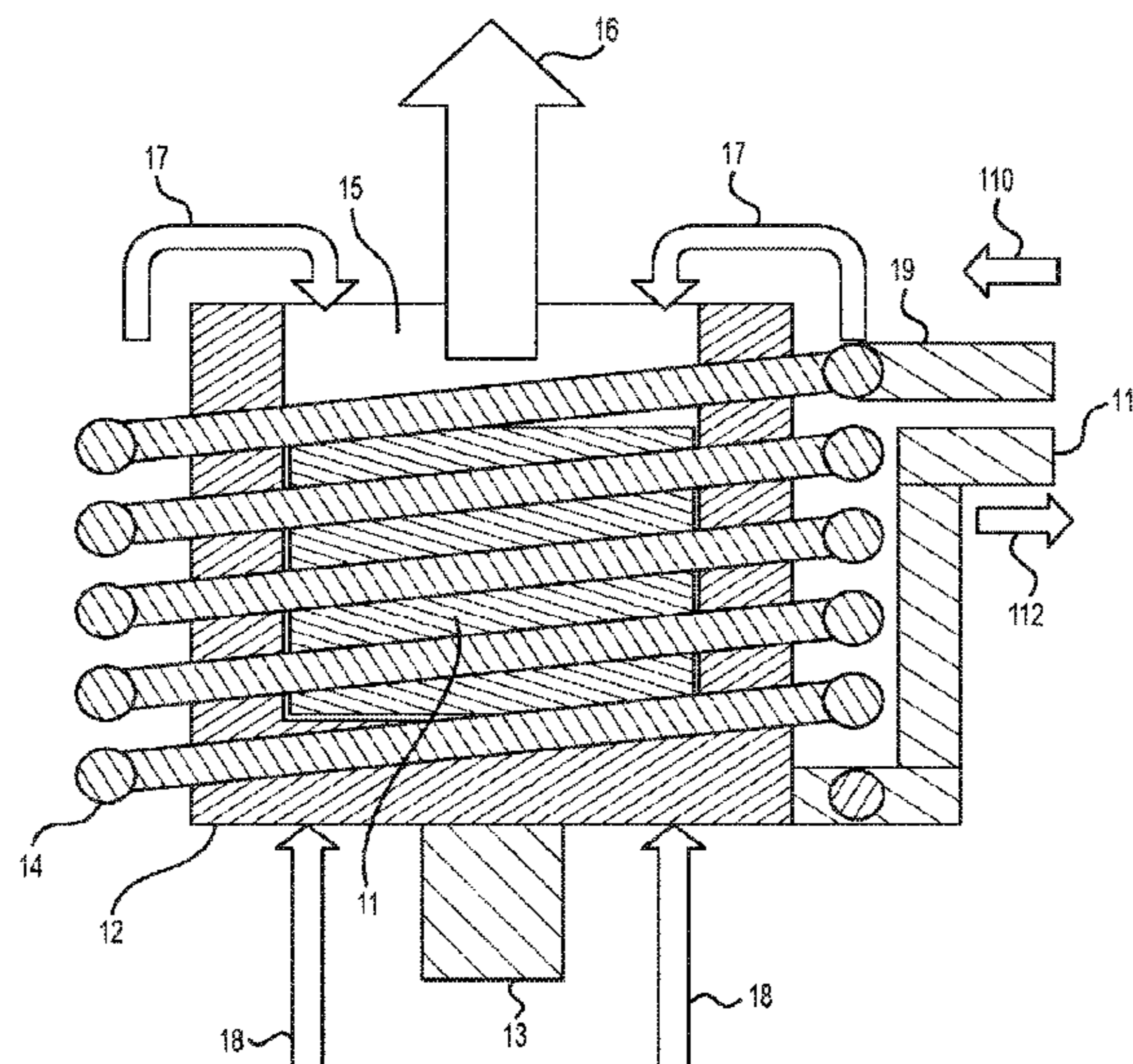
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(57) **ABSTRACT**

High quality, catalyst-free boron nitride nanotubes (BNNTs) that are long, flexible, have few wall molecules and few defects in the crystalline structure, can be efficiently produced by a process driven primarily by Direct Induction. Secondary Direct Induction coils, Direct Current heaters, lasers, and electric arcs can provide additional heating to tailor the processes and enhance the quality of the BNNTs while reducing impurities. Heating the initial boron feed stock to temperatures causing it to act as an electrical conductor can be achieved by including refractory metals in the initial boron feed stock, and providing additional heat via lasers or electric arcs. Direct Induction processes may be energy efficient and sustainable for indefinite period of time. Careful heat and gas flow profile management may be used to enhance production of high quality BNNT at significant production rates.

20 Claims, 9 Drawing Sheets



Related U.S. Application Data

continuation of application No. 15/576,050, filed as application No. PCT/US2016/023432 on Mar. 21, 2016, now Pat. No. 10,442,691.

(60) Provisional application No. 62/194,972, filed on Jul. 21, 2015, provisional application No. 62/164,997, filed on May 21, 2015.

(51) **Int. Cl.**

B01J 19/00 (2006.01)
B01J 19/24 (2006.01)
C04B 35/622 (2006.01)
B82Y 30/00 (2011.01)
H04W 4/021 (2018.01)
H04W 48/04 (2009.01)
H04W 72/04 (2009.01)

(52) **U.S. Cl.**

CPC . **C04B 35/6229** (2013.01); **B01J 2219/00132** (2013.01); **B82Y 30/00** (2013.01); **C01P 2004/01** (2013.01); **C01P 2004/04** (2013.01); **C01P 2004/13** (2013.01); **C04B 2235/386** (2013.01); **C04B 2235/404** (2013.01); **C04B 2235/421** (2013.01)

(58) **Field of Classification Search**

CPC H04W 72/04; H04W 72/0406; H04W 72/042; H04W 72/044; H04W 72/0446; B01J 10/00; B01J 10/005; B01J 19/00; B01J 19/0006; B01J 19/0013; B01J 19/24; B01J 2219/00; B01J 2219/00048; B01J 2219/00051; B01J 2219/0132; B01J 2219/24; C01P 2004/00; C01P 2004/01; C01P 2004/04; C01P 2004/13

See application file for complete search history.

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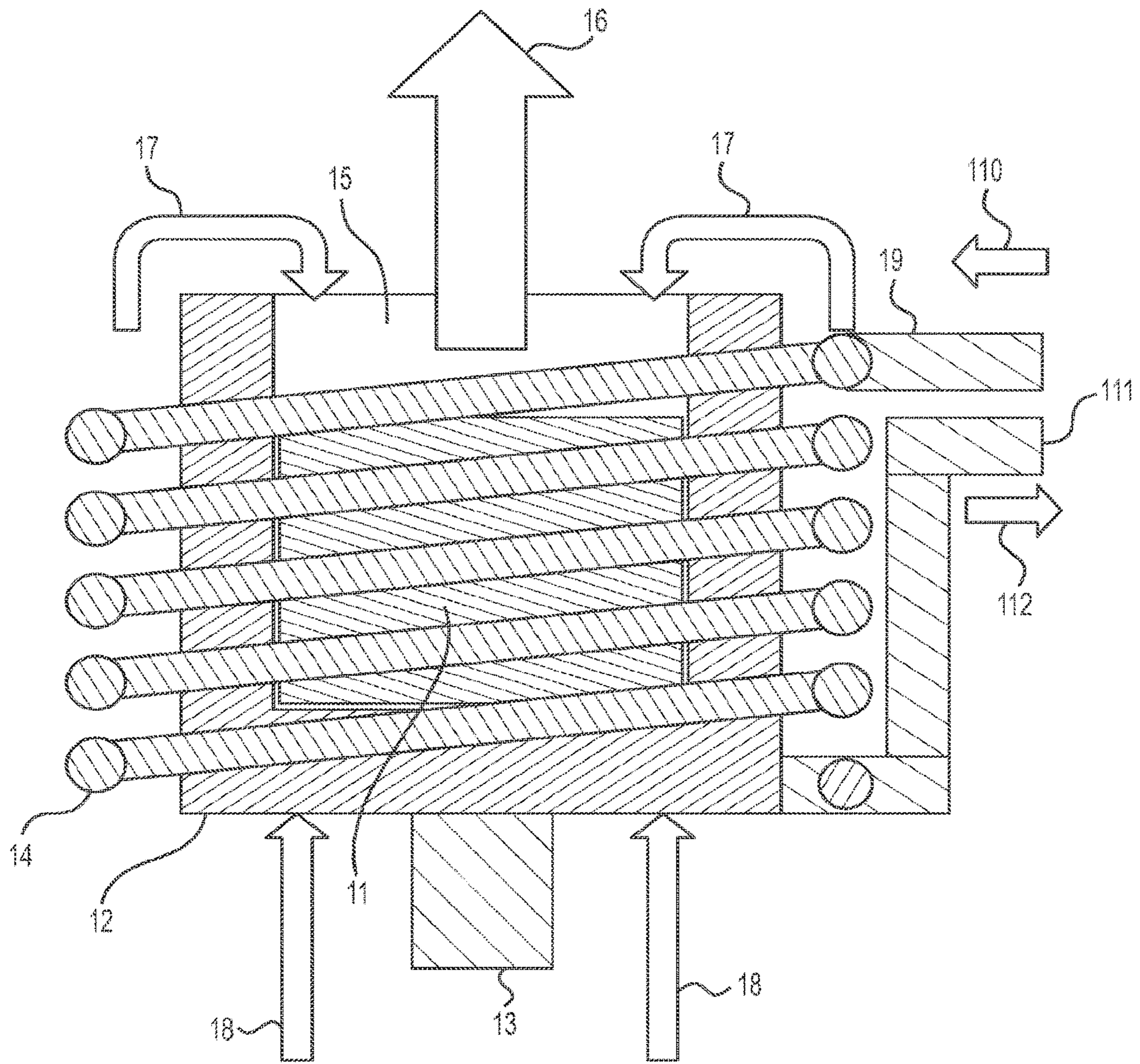


FIG. 1

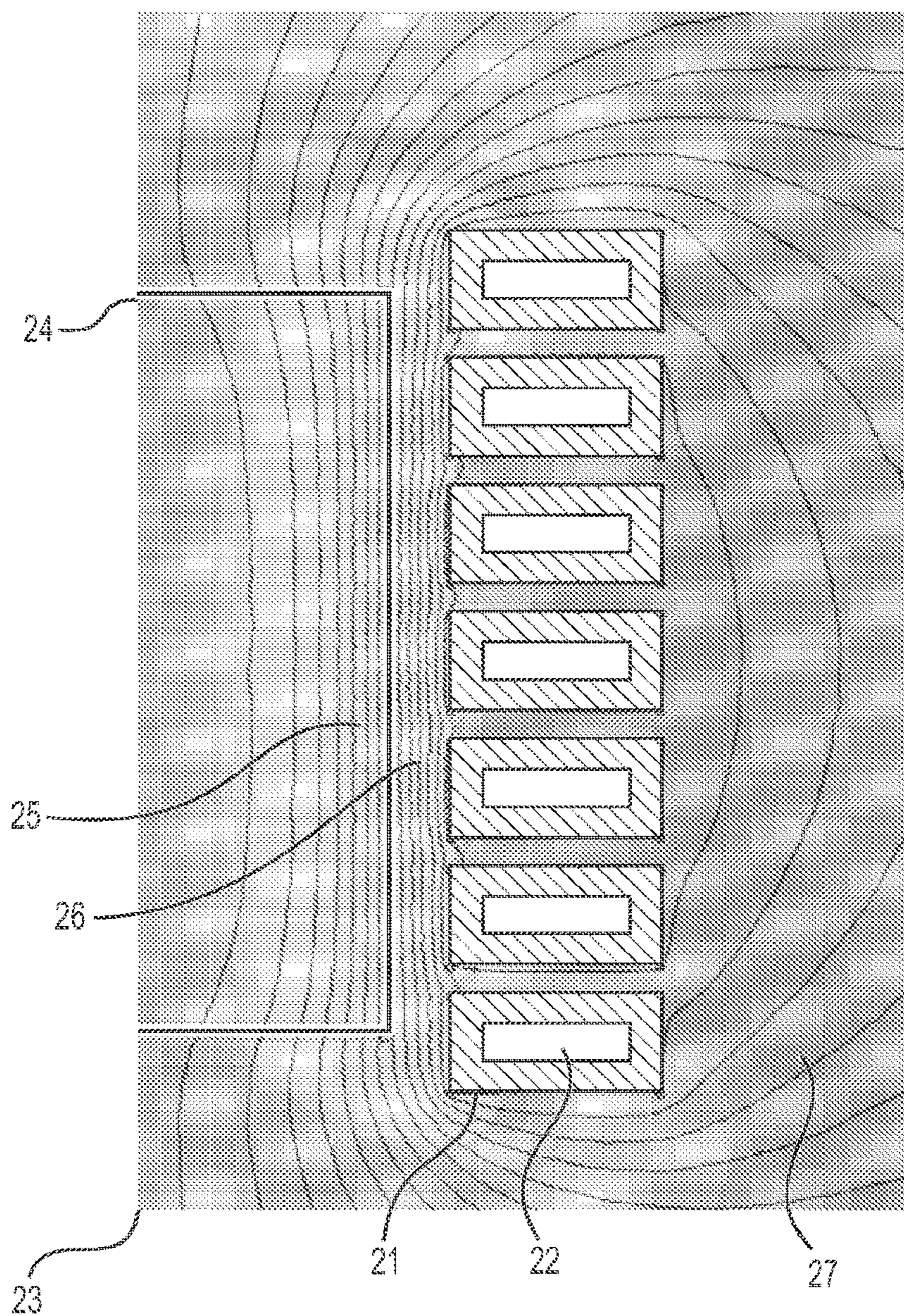


FIG. 2

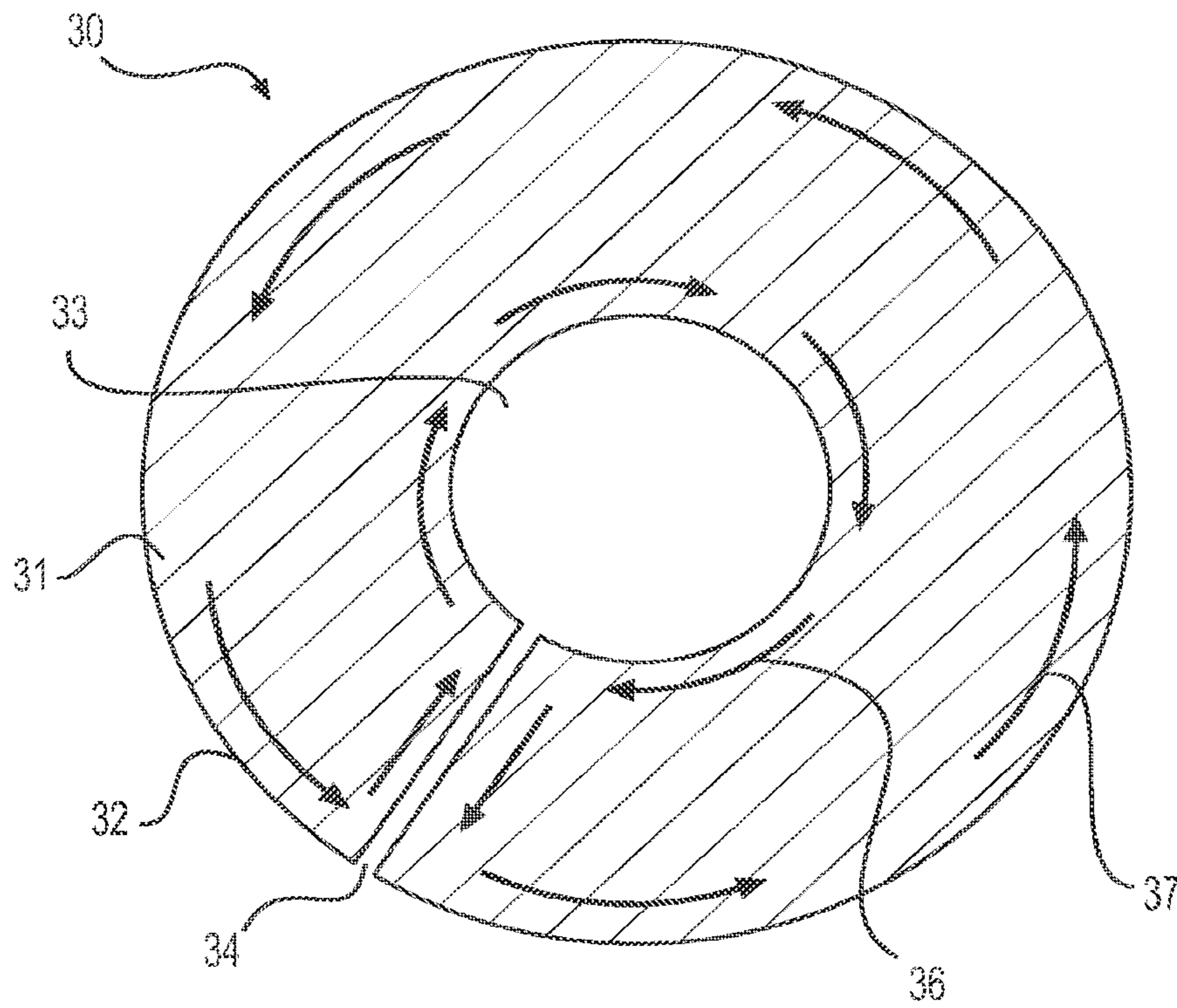


FIG. 3A

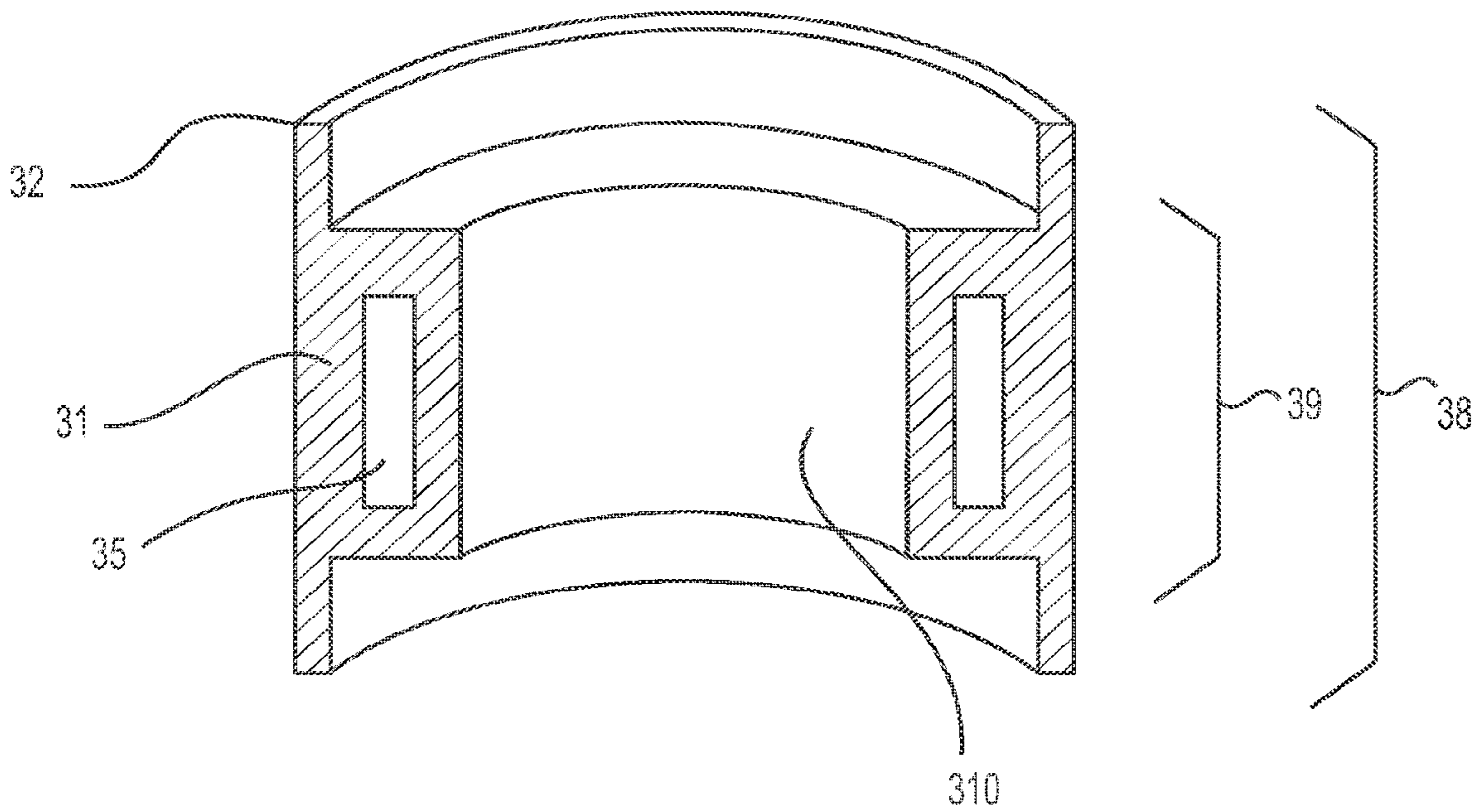


FIG. 3B

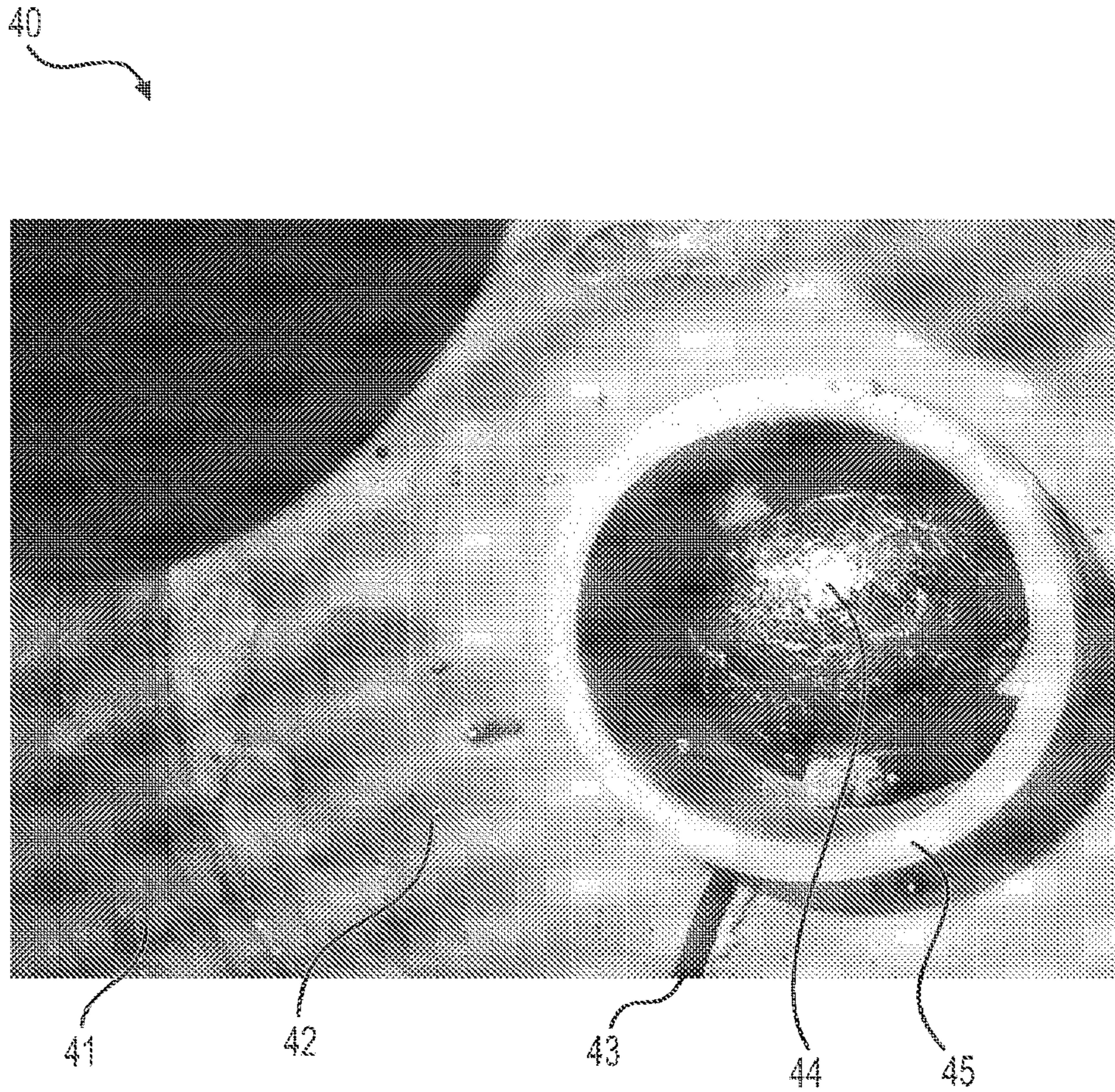


FIG. 4

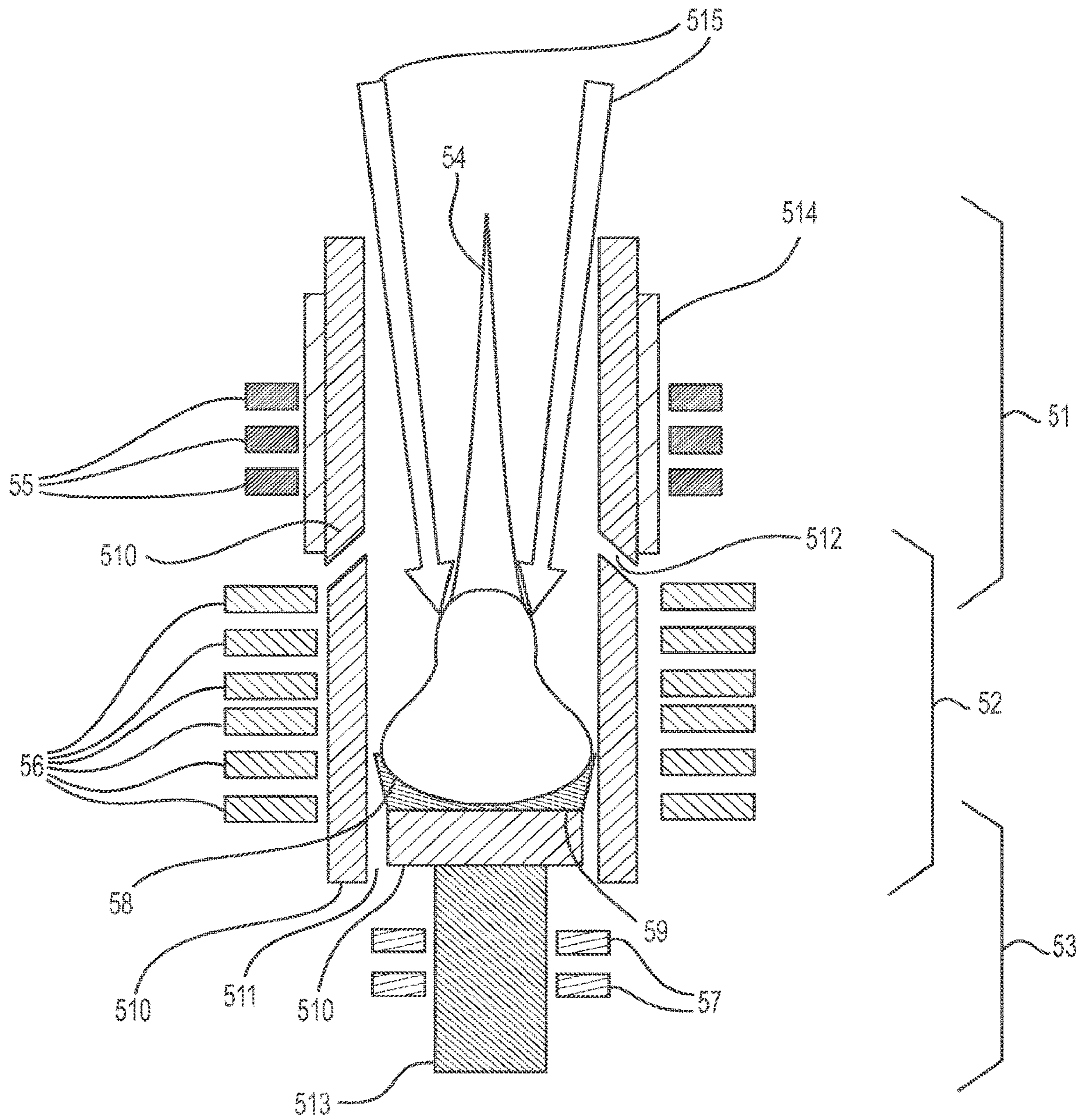


FIG. 5

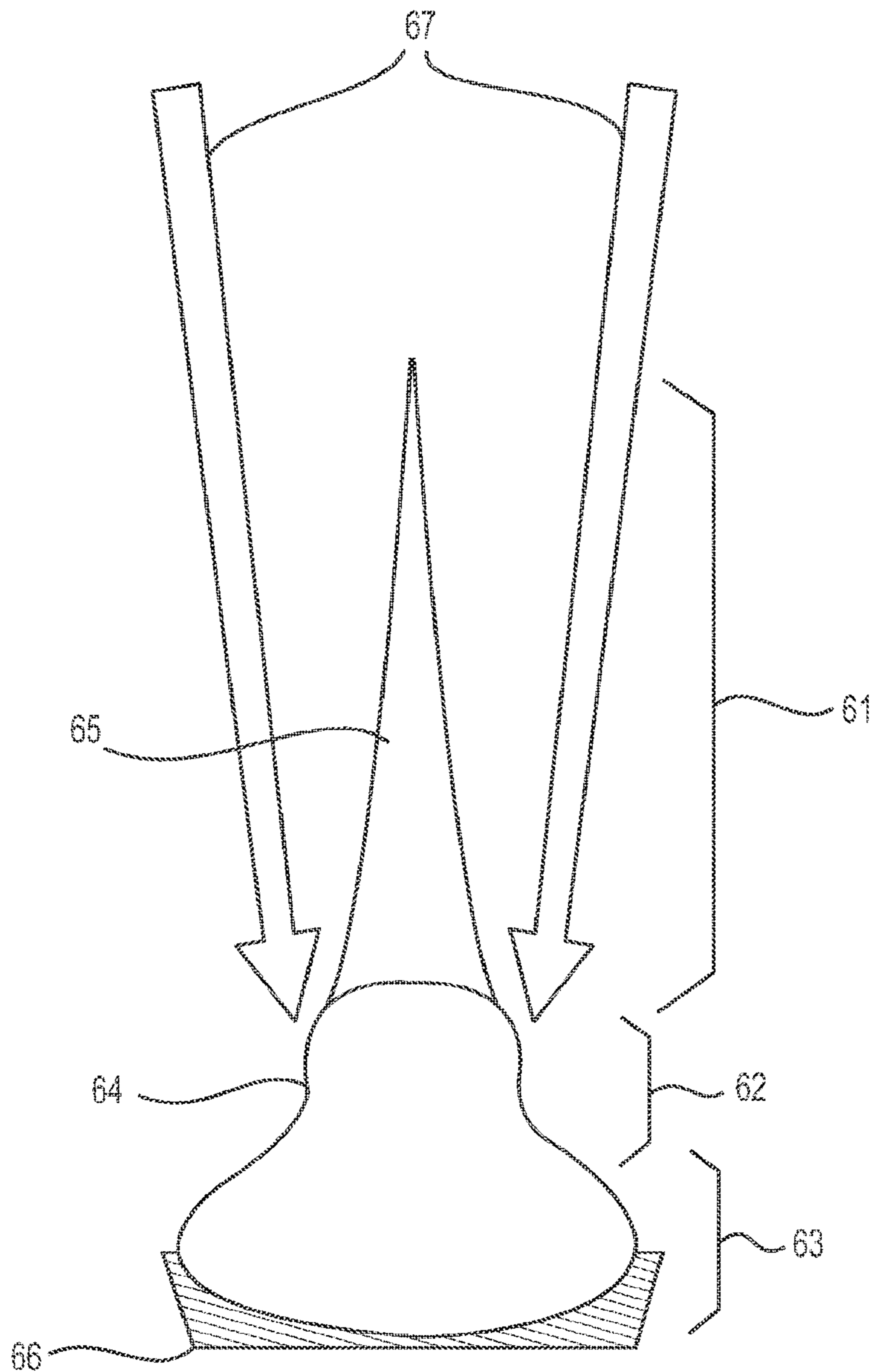
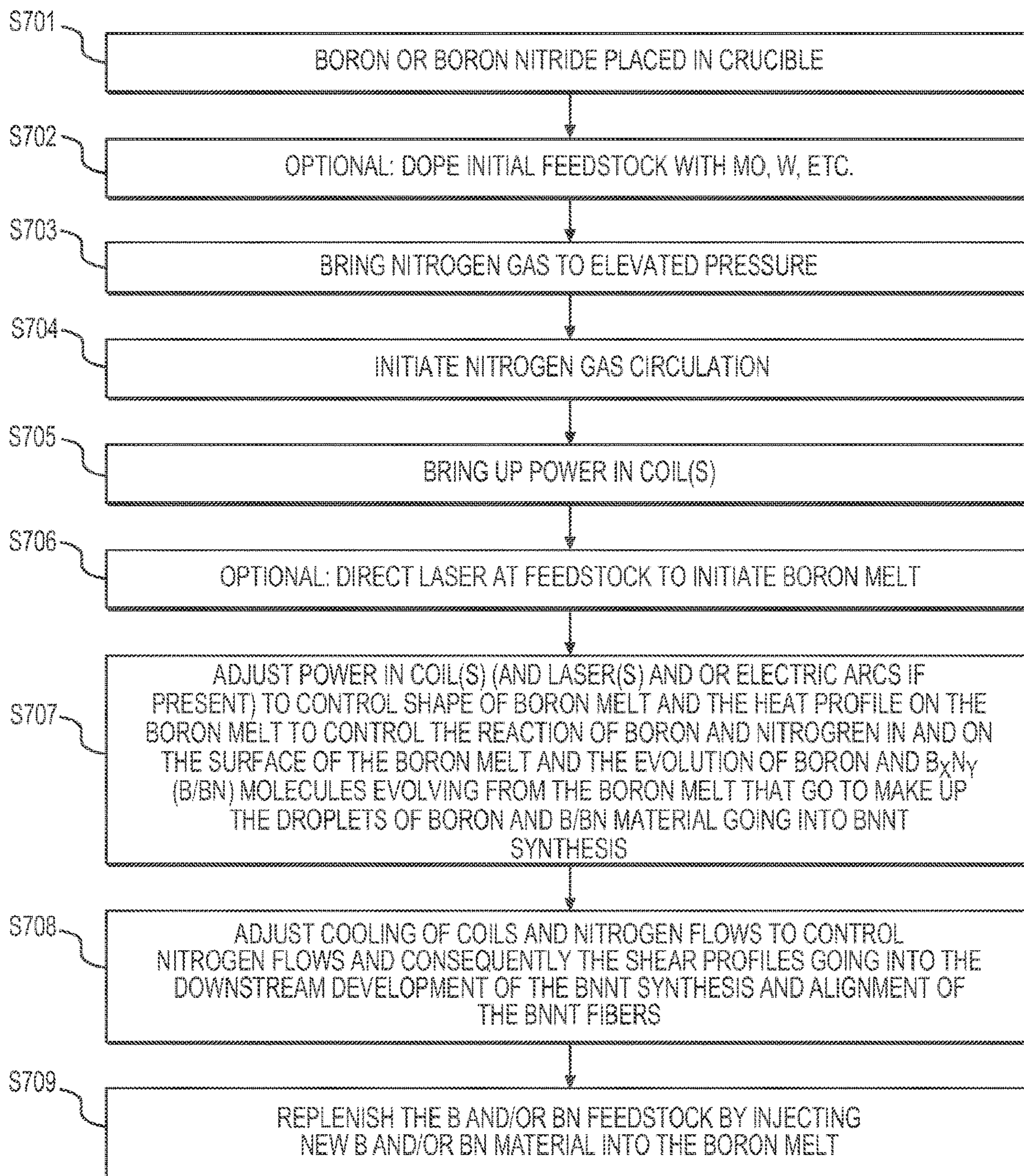


FIG. 6

**FIG. 7**

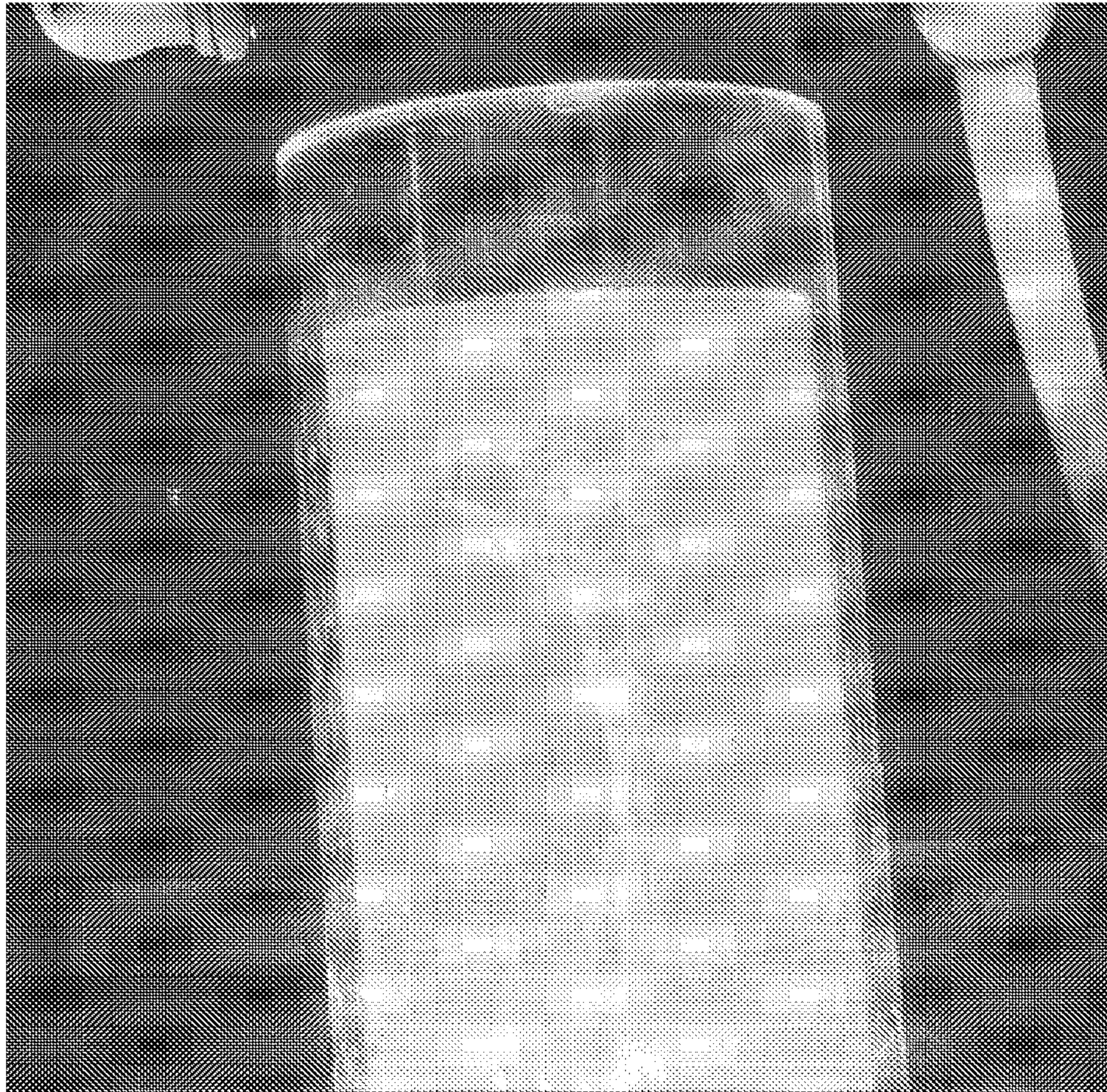


FIG. 8

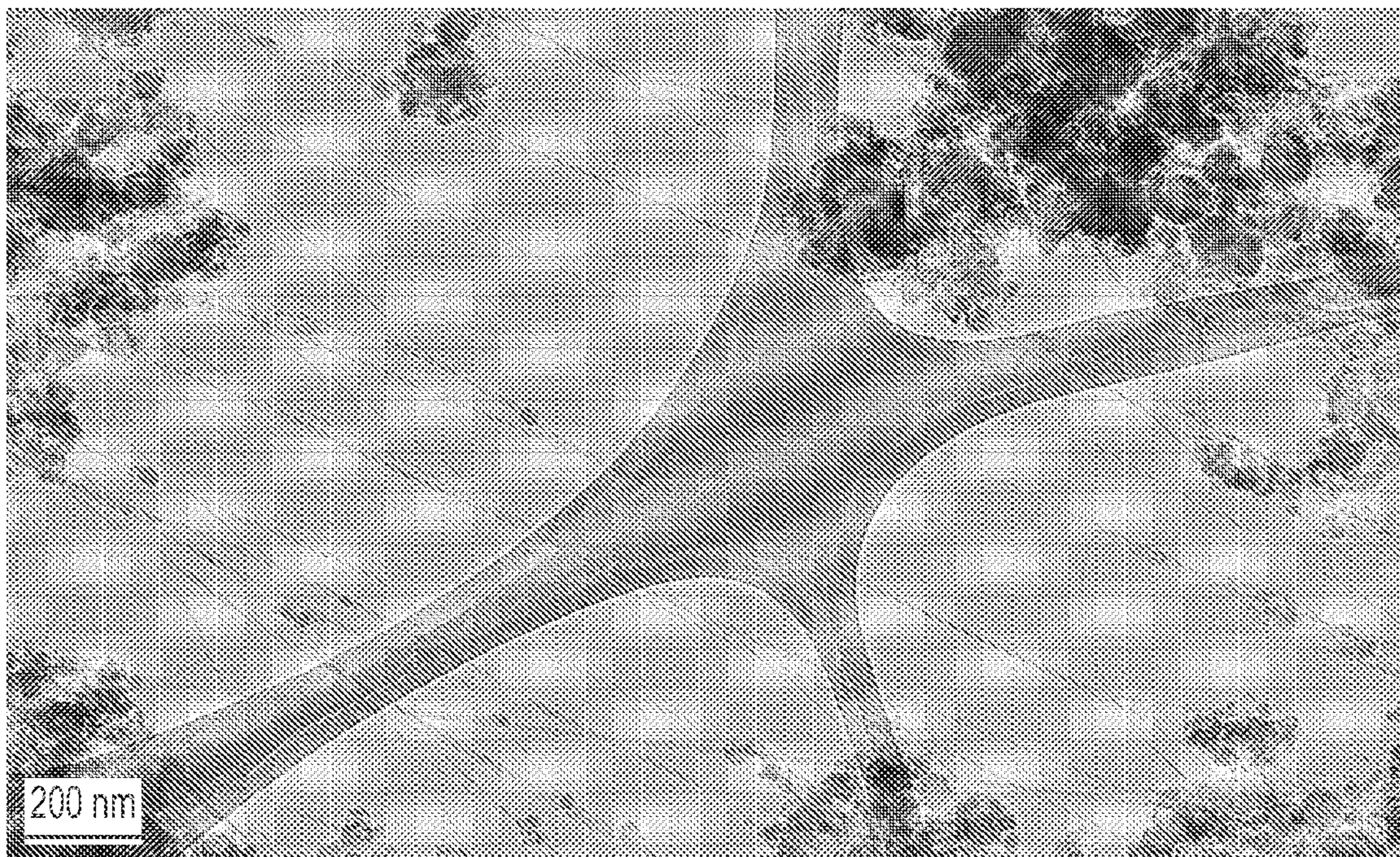


FIG. 9

BORON NITRIDE NANOTUBE SYNTHESIS VIA DIRECT INDUCTION

This application is a Continuation of application Ser. No. 16/561,091, filed Sep. 5, 2019, which is a Continuation of application Ser. No. 15/576,050, filed Nov. 21, 2017, now U.S. Pat. No. 10,442,691, issued Oct. 15, 2019, which is a National Stage Entry of International Application No. PCT/US16/23432, now WO/2016/186721 filed Mar. 21, 2016, which claims the benefit of U.S. Provisional Patent Application No. 62/194,972 filed Jul. 21, 2015, which claims the benefit of U.S. Provisional Patent Application No. 62/164,997, filed May 21, 2015, of which are hereby incorporated by reference in their entirety.

STATEMENT REGARDING GOVERNMENT SUPPORT

None.

FIELD

The present disclosure generally relates to synthesizing boron nitride nanotubes (BNNT), and in particular generating boron melts and enhancing the synthesis of boron nitride nanotubes using Direct Induction processes.

BACKGROUND AND SUMMARY

Synthesizing boron nitride nanotubes (BNNTs) that are highly crystalline with few defects, and that are few-wall with aspect ratios generally exceeding 10,000 or even a 1,000,000 to 1, require stable and well-controlled self-assembly regions that are typically at high temperature. Minimizing boron and boron nitride impurities in the BNNT material produced in these synthesis processes is important for many potential uses of such BNNTs. In addition, manufacturing BNNTs in the quantities needed for many applications is an increasingly important consideration.

For the creation of BNNTs in the form of long fibers, yarns, or strings, the purity and alignment of the BNNTs is often dominated by the quality of the BNNT material in the synthesis process, as taught in International Patent Application Ser. No. PCT/US2015/27570. Current laser processes, such as described in International Patent Application Ser. No. PCT/US2015/58615, and Inductively Coupled Plasma (ICP) processes, such as described in International Patent Application Ser. No. PCT/US2014/63349, have demonstrated that they can produce BNNTs of desirable quality. However these processes may have limitations due to energy efficiency and limitations due the levels of impurities of boron particles, amorphous boron nitride (amorphous BN) particles and hexagonal boron nitride (h-BN) particles.

Generally, BNNT structures may be formed by thermally exciting a boron feedstock in a chamber in the presence of nitrogen gas. Unlike carbon nanotubes (CNTs), U.S. Pat. No. 8,206,674 to Smith et al., incorporated by reference in its entirety, indicates that BNNTs form without the presence of chemical catalysts, and preferably at elevated pressures of about 2 atm to about 250 atm. CNTs, on the other hand, typically require the presence of chemical catalysts such as metal catalysts. It has been shown that BNNTs do not form in the presence of such catalysts, indicating that the formation of BNNTs is fundamentally different than the formation of CNTs.

Most contemporary BNNT synthesis methods have severe shortcomings, including one or more of having low

yield, short tubes, discontinuous production, poor crystallinity (i.e., many defects in molecular structure), and poor alignment. Additionally, many contemporary BNNT synthesis methods do not produce high quality BNNTs. Although there is no agreed upon standard in the scientific literature, the term ‘high quality’ BNNTs generally refers to long, flexible, molecules with few defects in the crystalline structure of the molecule. Apart from the Applicant’s processes, there are no other reports of the synthesis of continuous BNNT fibers or BNNT strands, particularly having few defects and good alignment. The BNNT “streamers” described in U.S. Pat. No. 8,206,674 to Smith et al., for example, form near a nucleation site such as the surface of the boron feedstock, but were limited to about 1 cm in length. BNNT “streamers” at such lengths are inadequate for producing BNNT fibers and yarns.

What is needed are apparatus, systems, and methods, for the continuous production of BNNT fibers and BNNT strands, having few defects and good alignment. The Applicant has described such apparatus, systems, and methods in related applications. For example, in International Patent Application No. PCT/US15/27570 (incorporated by reference in its entirety), Applicant describes, inter alia, the continuous formation of BNNT fibers, BNNT strands, and BNNT yarns. In that disclosure, Applicant provides embodiments in which one or more lasers provide thermal excitation for generating a boron melt.

While driving the synthesis of high quality BNNT via laser driven embodiments is effective, as described in International Patent Application Ser. No. PCT/US2015/58615, the laser driven processes are relatively inefficient from the conversion of electrical energy, or other forms of energy, into the final high quality BNNT, and consequently can be difficult to scale to very high powers. For example, known laser driven BNNT synthesis systems are less than 5 kW average power.

For decades radio frequency (RF) Induction technology has been utilized to melt materials at power levels ranging from watts to megawatts. Items ranging in size from less than a finger ring to large vats of material have melted. However, RF technology has not been used for synthesizing BNNTs at high temperatures, i.e. above the melting point of boron, and in particular has not been implemented for synthesizing high quality BNNTs. When RF Induction is utilized for heating a boron melt to synthesize high quality BNNTs, RF Induction will be referred to as Direct Induction.

RF Induction heating is commonly used to heat solids for the purposes of surface modification. This can result in solid-state reactions within the solid (for example, the heat treatment process of austenitization, which may occur only at the surface or at any depth within the material) or processes in which the surface reacts with an atmosphere (carburizing, nitriding, boriding, etc.) RF Inductive heating applications such as forging or welding are not relevant here. RF Induction heating is also used extensively to melt metals for refining, alloying, and casting operations. While RF Induction heating has recently been used to process non-conductive nonmetals that become conductive at high temperatures (for example, silicon crystal growth, crystal refinement, or skull melting of cubic zirconia, etc.), in these applications all of the chemical reactions take place within the melt.

Additionally, Direct Induction has not been utilized for the synthesis or carbon nanotube (CNT) self assembly process. It should be noted that the processes and systems described herein do not apply to the formation of carbon nanotubes (CNTs). High temperature BNNT synthesis pro-

cesses and systems generally involve forming a liquid material, referred to herein as a boron melt, from a boron feedstock, in more or less steady state and at very high temperature, in a nitrogen environment at an elevated pressure, such that the process produces combination of the liquid material and the gas, without involving catalysts or other elemental chemically reactive species. On the other hand, CNTs synthesis usually requires metal catalyst or other elements such as hydrogen that do not end up in the CNTs except as impurities. Certain arc discharge and laser processes will make limited quantities of CNTs, usually in vacuum, low pressure environments of hydrocarbon gases or inert gases. As a final example of the differences between the synthesis of BNNT and CNT, a CNT synthesis processes involve having a steady state ball of liquid carbon without catalysts would minimally require a temperature of 4,300° C. just to achieve the liquid carbon state and a temperature higher than this to achieve any level of CNT self assembly in a region of pure carbon gas that would have to be at a nearly equally high temperature.

Accordingly, what is needed are energy-efficient apparatus, systems, and methods, for synthesizing BNNTs, including high quality BNNTs. Further, such apparatus, systems, and methods, should be capable of synthesizing BNNTs at sufficient manufacturing quantities to enable numerous applications of BNNTs. Additionally, such apparatus, systems, and methods, should be capable of producing BNNT fibers, strings, and yarns, including highly aligned BNNT fibers, strings, and yarns.

SUMMARY

Described herein are apparatus, systems, and methods, for synthesizing BNNTs, including high quality BNNTs, incorporating Direct Induction processes.

There are a number of challenges to incorporating Direct Induction processes to synthesizing BNNTs. These challenges to using Direct Induction include: 1) the material being melted must be an electrical conductor, or alternatively be in an electrically conductive container; 2) boron and boron nitride feedstock materials are not electrically conductive at temperatures below 800° C., and are only minimally electrically conductive until they are in a molten state; and 3) high quality BNNT synthesis processes generally operate at temperatures above the melting temperature of boron nitride, 2,973° C.

Applicant has found solutions to these challenges for synthesizing BNNT using Direct Induction. By utilizing Direct Induction as a source of providing heat for the materials going into the BNNT self-assembly process, the indicated issues can be successfully addressed and desired quality and quantities of BNNT can be economically produced. The Direct Induction processes described herein are significantly more energy-efficient than ICP processes, and result in substantially fewer impurities. Unlike ICP processes, in which the plasma heats the gas phase, these Direct Induction processes supply heat to the boron feedstock. As a result, the processing challenges for the Direct Induction processes described herein are unique.

Indeed, until this disclosure, RF Induction has not been used to drive high temperature gas-phase chemical reactions external to the molten material as the primary end product of the process. The use of RF Induction heating in a chemical vapor deposition process is in many ways the opposite, as the reactions take place at the heated surface for the sole purpose of surface modification. In chemical vapor deposition (CVD) processes the RF Induction can be utilized to

heat the materials including their surfaces where the vapor is being deposited and or reacted through a variety of chemical reactions. For example, in the production of low quality BNNTs, i.e. typically 10 to 50 walls with many defects, BOCVD (boron oxide chemical vapor deposition) in several versions requires a metal oxide such as MgO or Li₂O in the precursor to act as a catalyst. RF Induction is used to heat a graphite susceptor that surrounds the reaction chamber to a temperature in the region of 1300° C.—well below boron nitride's melting point. As a result, CVD processes do not generate, involve, or result in anything similar to a boron melt, and thus would not be instructive in overcoming the challenges presented by Direct Induction processes.

Under the present approach, a process for synthesizing boron nitride nanotubes generally includes feeding nitrogen gas to a chamber in a first direction, and in some embodiments at an elevated pressure, and supplying power to a Direct Induction coil surrounding a boron feedstock to form a boron melt. The nitrogen gas flow may be controlled at various locations in the process, such as, for example, at the boron melt and through the growth zone. In some embodiments, at least one noble gas may be fed to the chamber, particularly during process start-up. Introducing a noble gas inhibits the formation of boron and boron nitride micro-droplets, which may be beneficial, until the full temperature of the boron melt is achieved. For example, inhibiting the formation during startup minimizes impurities. After the boron feedstock reaches the desired temperature, the noble gas feed to the chamber may be stopped, allowing the BNNT self assembly process to begin. Boron and boron nitride micro-droplets emerge from the boron melt downstream of the boron melt in the first direction, and BNNTs self-assemble downstream from the boron and boron nitride micro-droplets. In some embodiments, supplying power to the Direct Induction coil also causes a portion of the nitrogen gas entering the chamber to dissolve in the boron melt and form boron nitride molecules and subsequently boron and boron nitride micro-droplets.

The boron feedstock includes a material containing boron, and in some embodiments may also include a refractory metal. The refractory material may, for example, be molybdenum and/or tungsten. In some embodiments, the boron feedstock is supported in a crucible. The crucible, in turn, may be supported in by a Direct Induction coil, such as the Direct Induction coil surrounding the boron feedstock, and in some embodiments may be supported by a Direct Induction eddy current field concentrator. The crucible may be cooled in some embodiments, such as through convective cooling, water cooling, air cooling, contact cooling with the crucible, among other techniques known in the art.

In some embodiments, a layer of boron nitride may be deposited under the boron feedstock. In some embodiments, the boron feedstock may be heated to form an electrically conductive boron feedstock. For example, supplemental heating, such as with a laser and/or an electric arc, may be used to raise the temperature of the boron feedstock such that the boron feedstock becomes electrically conductive.

In embodiments of the present approach, an apparatus for synthesizing BNNTs may include a chamber providing a boron feedstock mounting surface, a nitrogen gas supply system configured to feed nitrogen gas, in some embodiments at an elevated pressure, to the chamber in a first direction, a boron feedstock support, and a Direct Induction coil surrounding the boron feedstock support.

Embodiments may include a growth zone region downstream of the boron feedstock support in the first direction,

in which BNNTs self-assemble downstream of the boron feedstock support in the first direction. The boron feedstock support may be a crucible, and in some embodiments the crucible may be made of, among other materials, boron nitride.

Some embodiments of the apparatus may also include a Direct Induction eddy current field concentrator. Generally, the concentrator comprises an outer cylindrical portion of a first length in the first direction, and an inner cylindrical portion of a second length in the first direction, the first length being greater than the second length. The concentrator may include a vertical slot configured to force eddy currents generated in the Direct Induction concentrator to follow a circulating path. The concentrator may be configured to house the crucible. In some embodiments, a Direct Induction coil may be configured to house the crucible.

In some embodiments, the apparatus may include a second Direct Induction heating coil surrounding at least a portion of the boron feedstock support. The second Direct Induction coil may also be used to heat a portion of the growth zone, in which BNNTs self-assemble. Some embodiments may include a supplemental heat source, such as at least one laser or electric arc. The supplemental heat source may be used to heat the boron feedstock and boron melt, and cause the boron feedstock to behave electrically conductive. Some embodiments may include a direct current heating coil surrounding at least a portion of the growth zone to control the temperature profile in the growth zone.

DRAWINGS

FIG. 1 illustrates an embodiment of an apparatus for synthesizing BNNTs using Direct Induction.

FIG. 2 shows a simulation of the electromagnetic field intensity around a cross-section of a Direct Induction coil.

FIGS. 3A and 3B illustrate a concentrator and its electrical current and cooling water flows according to an embodiment of the present approach.

FIG. 4 is a photograph showing a concentrator containing a cooled boron melt generated using an embodiment of the present approach.

FIG. 5 illustrates an embodiment of an apparatus for synthesizing BNNTs using Direct Induction.

FIG. 6 illustrates an enlarged view of an aspect of an embodiment of an apparatus for synthesizing BNNTs using Direct Induction.

FIG. 7 is a flow chart for synthesizing BNNTs using Direct Induction according to an embodiment of the present approach.

FIG. 8 is a photograph showing BNNTs synthesized using Direct Induction according to an embodiment of the present approach.

FIG. 9 shows a transmission electron microscopy image of BNNTs synthesized using Direct Induction according to an embodiment of the present approach.

DESCRIPTION

The following description is of the best currently contemplated modes of carrying out exemplary embodiments of the present approach for synthesizing boron nitride nanotubes, and in particular generating boron melts and enhancing the synthesis of boron nitride nanotubes using Direct Induction. The description is not to be taken in a limiting sense, and is made merely for the purpose of illustrating the general principles of the present approach.

BNNT synthesis by high temperature processes generally requires heating boron to a liquid boron melt, typically to a temperature near elemental boron's melting point, i.e. the point at which boron (B) and molecules of boron-nitrogen (B_xN_y) are evaporated from the boron melt, the combination referred to as B/BN in this description. The boron feedstock is heated to a boron melt in a nitrogen atmosphere. The operating pressure may be from a tenth of an atmosphere to about 250 atmospheres, including, for example, about 1 atmosphere to about 12 atmospheres. Although capable of synthesizing BNNT at elevated pressures of about 2 atmospheres to about 250 atmospheres, Direct Induction driven processes also synthesize BNNT at lower pressures, including the elevated pressures useful in laser driven and catalyst-free Inductively Coupled Plasma processes. Additionally, noble gases such as helium, neon, argon, krypton and/or xenon may be present for some stages of the Direct Induction processes such as during initial heating of the boron feed stock. The noble gas(es) interfere with the BNNT self-assembly by replacing nitrogen molecules available for reaction, thereby starving the reaction. Increasing noble gas fractional pressure slows the formation of boron and boron nitride micro-droplets and slows the BNNT self-assembly rate, and at high enough fractional pressure will halt the BNNT self assembly and the formation of boron, amorphous BN and h-BN. It should be appreciated that these gases are not serving as catalysts, but instead may be used to control the rate of BNNT formation and the rate of formation of impurities of boron, amorphous BN and h-BN. Minimizing the rate of formation until the boron melt has achieved its operating temperature advantageously reduces impurities in the synthesized BNNTs.

Direct Induction works by setting up a transformer where alternating current (AC) in a primary coil transfers electrical power to induced currents in a secondary conductor. The induced AC currents flowing in the secondary conductor, heat the secondary conductor via resistive heating. More complex Direct Induction involves inserting an intermediary coil, coils, or concentrator, such that there are three or more layers in the resultant transformer.

Generally, processes for generating BNNT through high temperature methods involve three zones in a chamber. This application refers to these heat zones as preheat-support zone, boron melt zone, and BNNT growth zone. The preheat-support zone is configured to allow nitrogen gas to flow into the chamber at an elevated pressure. In some embodiments, the nitrogen gas may be flowing in a flow direction, relative to the melt zone and the growth zone. The boron melt zone is configured to transmit heat to a boron feedstock on a target holder. The heat will form a boron melt from the feedstock, and thus the target holder must be configured to handle the phase transition from the initial feedstock to the boron melt. Boron and boron nitride micro-droplets, including BBN, evaporate from the boron melt, and BNNTs will self-assemble in the growth zone. In embodiments using nitrogen gas flowing in a flow direction, the micro-droplets will both form and evaporate downstream of the boron melt, and the BNNT growth zone will also be downstream of the boron melt. It should be noted that in some embodiments, there may be a gradual transition and/or overlap between zones. Also, any transition and/or overlap between zones may change during operation, such as, for example, from start-up to continuous production. As the Direct Induction power levels and field configurations are adjustable during operation, the power going into the boron melt can be controlled both in terms of total power and power distribu-

tion. In turn, the power distribution can be controlled to assist in driving the BNNT self assembly process.

FIG. 1 illustrates an embodiment of an apparatus for synthesizing BNNTs from a boron feedstock using Direct Induction. In this embodiment, the boron melt **11** rests on a crucible **12**. The crucible **12** is positioned in a chamber (not shown), and may, in some embodiments, be supported on a post **13**. The Direct Induction primary coil **14** surrounds the crucible **12**. The number of turns in primary coil **14** in this embodiment is merely demonstrative, as the coil parameters will vary depending on the embodiment. After the boron feedstock has been converted to boron melt **11**, the boron melt **11** evolves molecules of B/BN into the region **15** above and around boron melt **11**, and into the BNNT self-assembly region **16**. Based on the orientation shown in FIG. 1, nitrogen gas enters the process from below crucible **12** as illustrated by arrows **18** through holes (not shown) in the crucible **12**. Also, nitrogen gas may enter the process from the crucible **12** above as illustrated by arrows **17**. Electrical alternating current power and water cooling flow in and out of the coil **14** from external feeds **19** and **111** as indicated by the arrows **110** and **112**. The coil **14** is acting as the primary and the boron melt **11** is acting as the secondary in this embodiment.

FIG. 2 shows a simulation of the electromagnetic field intensity around a cross-section of a Direct Induction coil. The electromagnetic field lines of a Direct Induction coil **21** with its water cooling channels **22** are visible to one side of the center line **23** (the remainder of the apparatus is omitted for ease of demonstration). The region near the boron melt **24** shows how the outer edges of the boron melt region **25** experience the nearby field **26** from the Direct Induction coil **21**. The feedback of the boron melt **24** on the local fields **25** and **26** has not been included in the simulation. The outside field **27** is substantially less strength. As one of ordinary skill will appreciate, the dimensions of the coil **21** including the geometry of the tubing forming the coil **21**, the size of the boron melt region **24**, the spacings between the components, and the frequency and power level of the alternating current, contribute to the strength of the electromagnetic fields generated in the boron melt region **24**. Thus, these parameters may be adjusted to suit a specific embodiment of the present approach so as to optimize the temperature distribution of the boron melt **11** and the temperature distribution of the BNNT self assembly region **16**.

Some embodiments may include a Direct Induction eddy current field concentrator that operates as a secondary coil, thereby effectively adding an additional loop. Some embodiments may find a Direct Induction eddy current field concentrator useful to achieve the desired heat profile in the region of the boron melt. FIGS. 3A and 3B illustrate a concentrator **30** and its electrical current **36** and **37** flows and cooling water channels **35** according to an embodiment of the present approach. The concentrator **30** may be utilized as an element in a Direct Induction transformer. The outer portion **32** of a Direct Induction concentrator **30** in FIGS. 3A and 3B is cylindrical in this embodiment, and concentrator **30** is approximately the height **38** of the Direct Induction primary coil **14** in FIG. 1. The inner portion of the Direct Induction concentrator **31** has an open center **33** for receiving the boron melt **11** and its crucible **12**, and the height **39** of the inner portion **31** is less than the height **39** of the outer portion **32** such that the highest level of current is on the inner surface **310** of the concentrator **30**. As shown in FIG. 3A, a vertical slot **34** may be placed in the Direct Induction concentrator **30**. Slot **34** forces eddy currents generated in the Direct Induction concentrator **30** by the currents in the

Direct Induction primary coil **14** (not shown in FIG. 3) to follow a circulating path as by the arrows **36** and **37**. The circulating path is a result of the Lorentz forces between the inner **36** and outer **37** eddy currents. The currents generated in the boron melt **11** (not shown in FIG. 3) mostly come from the inner eddy currents **36** in the Direct Induction concentrator **30**. As one of ordinary skill in the art should appreciate, the shape of the fields in the region **33** of the boron melt **11** can be controlled by the relative ratio of the height **38** of the outer portion **32** to the height **39** of the inner portion of the Direct Induction concentrator **31**, as well as the inner radius profile **310** of the inner portion **31** of the Direct Induction concentrator **30**. Typically the Direct Induction concentrator **30** is made of copper, but other highly electrically and thermally conductive materials can be considered.

FIG. 4 shows a close-up image of a portion of a prototype Direct Induction concentrator **40** in which a boron melt **44** was generated from a boron feedstock using Direct Induction. This image shows the boron melt **44** cooled in the boron nitride crucible **45**. The prototype concentrator **40** housed the boron nitride crucible **45** as described above. For clarity, only the outer portion **41** of the concentrator **40**, the inner portion **42** of the concentrator **40** and the slot **43** in the concentrator **40** are shown. The remainder of the prototype apparatus is not visible in FIG. 4.

FIG. 5 illustrates an embodiment of an apparatus for synthesizing BNNTs using Direct Induction. The embodiment shown in FIG. 5 may be configured to synthesize high quality BNNT, and may include one or more additional sources of heating to control the synthesis process. There are three overlapping zones illustrated in FIG. 5:

1) The preheat-support zone **53** may include physical support post **513** for the boron feedstock (e.g., at start-up), and also for the generated boron melt **58** (e.g., after initial heating and during generally steady-state operation). In some embodiments, the boron melt **58** may be large enough to require physical or mechanical support in the apparatus, and thus in some embodiments the physical support **513** may support a boron nitride crucible **510** holding the boron melt **58**. The preheat zone **53** may in some embodiments include a Direct Induction or direct current heating coil **57** for the support post **513**. Alternatively, in some embodiments the support post **513** may require water cooling and the coils shown **57** may be for water rather than electrical currents. The selection of cooling or heating the support post **513** in a particular embodiment depends on the specific embodiment, including, for example, the size and weight of the particular apparatus and the potential benefit of heating or cooling the free, unoccupied space in the pre-heat support zone to optimize the nitrogen flows. Some embodiments may include pre-heating the nitrogen gas flowing into the pre-heat support zone.

2) The boron melt zone **52** is the zone in an apparatus in which heat is introduced to the boron melt **58**. As described above, during start-up the heat raises the boron feedstock temperature to generate a boron melt **58**, and then during operation maintains the boron melt **58** at its smoking point, i.e., temperature above which the boron melt **58** evolves boron and boron-nitrogen molecules, B_xN_y ("B/BN"). The B/BN molecules flow into the BNNT growth zone **51**, in which BNNTs self-assemble from the B/BN molecules and associated B/BN liquid droplets. Self-assembly occurs predominantly downstream of the boron melt **58**, although the location of the BNNT growth zone **51** will depend on the particular embodiment and operating conditions. The Direct Induction coil **56** holds the boron nitride crucible **510** and the Direct Induction coil **56** provides cooling to the boron

nitride crucible **510** from contact with the boron nitride crucible **510**. Boron nitride filler material, not shown, may be introduced between the Direct Induction coil **56** and the boron nitride crucible **510** and between the coils in the Direct Induction coil **56**. The boron nitride crucible **510** can be held below the melting temperature of boron nitride of 2,973° C., to reduce degradation of the crucible. The boron nitride crucible **510** may also be cooled by nitrogen gas entering the crucible, such as, for example, from openings below **511**, openings on the sides **512** and/or the opening at the top (see FIG. 1, arrows **17**). The boron melt **58** is also provided support from a crust **59** of boron and boron nitride material formed between the boron melt **58** and the boron nitride crucible **510** and the support post **513**. The crust **59** forms on boron melt **58** during start-up, although in some embodiments it may be advantageous to place the boron feedstock on a thin layer or bed of boron nitride powder on crucible **510**, to initiate formation of the crust **59**. In some embodiments, a laser, multiple lasers or electrical arcs **515** may be used to provide heat to the boron feedstock and/or boron melt **58** from an opening at the top of the boron nitride crucible **510**. There are at least two general reasons to have these supplemental sources of heat: 1) they may be useful in bringing the initial boron feedstock to a sufficiently high temperature above 800 C, where the boron feedstock becomes sufficiently electrically conductive for the electromagnetic fields from Direct Induction coil **56** to further increase the temperature of the boron feedstock to become a boron melt **58**; and 2) formation of high quality BNNTs requires control of the temperature profile of the BNNT self assembly region **54** such that the B/BN liquid droplets and associated B/BN molecules fully convert to BNNT rather than converting to boron particles, amorphous BN and/or h-BN. The supplemental sources of heat **515** can be utilized to provide heat to regions of the boron melt **58** such that a temperature profile in the self assembly region **54** has the optimal conditions for BNNT self assembly.

In some embodiments, cooling the crucible **510** may be performed during operation to prevent over-heating and degradation. In the process of providing the cooling to the boron nitride crucible **510**, the nitrogen gas entering the crucible (see FIG. 1, arrows **17** and **18**) is heated as it feeds into the chamber and proceeds toward the boron melt zone **52**. In addition, the nitrogen gas entering the chamber can also provide cooling to the support post **513**. The nitrogen gas flows throughout the chamber may thus be configured to assist in cooling structures of the apparatus.

3) In the growth zone **51**, B/BN molecules generally form B/BN micro-droplets downstream of the boron melt **58**. BNNTs self-assemble from the BBN micro-droplets, also downstream of the boron melt **58**. To maximize the self-assembly of BNNTs from the B/BN micro-droplets, the BNNT growth zone **51** temperature profile may be controlled to account for radiative and convective heat loss. For example, the upper portion of the boron nitride crucible **510** can be cooled as required by a combination of the nitrogen gas convectively flowing along external surfaces of the crucible **510**, nitrogen gas flowing into the openings **511** and **512** (if included) in the crucible **510**, and optionally also water-cooled copper (not shown) surrounding the upper portions of the crucible **510**.

In some embodiments it may be desirable to provide additional heat to the BNNT growth zone **51** in addition to the supplemental heat sources **515**. A refractory metal or graphite cylinder **514**, which may be surrounded by an additional Direct Induction coil **55**, can be used to add heat to the BNNT growth zone **51**. Alternatively, additional heat

can be supplied by other heat sources as are known in the art, such as, for example, alternating or direct current heaters (not shown), lasers, and the like. In some embodiments, there may be sufficient electrical conductivity in the growth zone **51** that Direct Induction or alternatively microwave heating (not shown) also feed heat into the growth zone **51**. Providing supplemental heat allows for managing the residence time of the B/BN micro droplets and B/BN molecules in the BNNT self assembly region **54**. For example, in some embodiments the laser(s) **515** are utilized to control the heat distribution of the upper portions of the boron melt **56**, the upper Direct Induction coil **55** is utilized to control heat going directly into the BNNT self assembly region. Further, as one of ordinary skill in the art will appreciate, the inner radius profiles, the detailed spacing of the coils elements going into the direction induction coils **55** and **56** and the frequency of the Direct Induction power can all be utilized to control the heat flowing into the processes of the boron melt **58** and the BNNT self assembly region **54**.

As illustrated in FIG. 5, the support zone **53**, melt zone **52** and growth zone **51** may all overlap in some embodiments. The frequencies utilized for the Direct Induction coils **55**, **56** and/or **57** if present do not have to be the same. Each coil **55**, **56** and/or **57** may have a frequency optimized for the conditions of the specific embodiment. As one of ordinary skill in the art should appreciate, Direct Induction frequencies and RF frequencies are dependent on the sizes and geometries of the components and the levels of power (heating) used in a particular embodiment. The radius of the inner surface of the Direct Induction concentrator if used may be varied with height so as to vary the heating and the Lorentz forces on the boron melt **58** so as to increase or decrease the heating in a given portion of the boron melt **58**, and further to increase or decrease the amount of levitation forces on the boron melt **58**. In general, the Lorentz forces will be in the direction of pushing in on the boron melt **58** and up on the boron melt **58**. If these forces are not managed then the boron melt **58** can become unstable and oscillate in the crucible **510**. These forces push inward against the boron melt **58**, which may be beneficial as it keeps the boron melt **58** in the crucible **510** from touching the walls of the boron nitride crucible **510**, particularly at operating temperatures in excess of boron nitride's melting point. The detailed shape, frequencies, power levels for the Direct Induction coil **56** size of the boron melt **58** should be considered to achieve stable operation. In some embodiments, a reverse turn may be included (not shown) to further inhibit levitation of the upper portions of the boron melt **58**. A reverse turn may be included in an additional coil, too. In some embodiments, the levitation forces may be utilized to levitate the boron melt **58** to a position slightly above the bottom of the boron nitride crucible **510**. This can be utilized to reduce the cooling coming from the boron nitride crucible **510**.

FIG. 6 illustrates an enlarged view of an aspect of an embodiment of an apparatus for synthesizing BNNTs using Direct Induction. Boron melt **64** and BNNT self-assembly in the growth zone **61** (also **53** in FIG. 5) are shown in more detail to demonstrate how to form the boron melt **64** from a feedstock, and control the temperature profile. As discussed above, Direct Induction is not useful unless the boron feedstock is electrically conductive. The boron feedstock may be heated to above 800 C, so that it is adequately electrically conductive, with one or more lasers **67** or electrical arcs. Alternatively, or additionally, the boron feedstock may include one or more refractory metals, such as of molybdenum, tungsten, or other refractory metal in the feedstock. The amount of refractory metal in the initial

boron feedstock depends on the mass of the initial boron feedstock, and may vary from a few percent to factors of five or more than the amount of boron as determined by weight. The amount of refractory metal needed is less if some of the refractory metal is relatively pure and not dispersed into the boron feed stock. If one or more refractory metals are used, they do not participate in the BNNT self-assembly as either reactants or catalysts, and only serve to provide a conductor that can be heated by the Direct Induction-induced eddy currents. If one or more lasers **67** is present, the beam may enter the apparatus from an angle such as shown in FIG. **6**, so as not to disrupt the self-assembly region **65** and BNNTs flowing downstream. The angle of laser **67** shown in FIG. **6** is merely demonstrative, and in practice the angle will depend on the specific embodiment. Additionally, it may in some embodiments be useful to have helium, neon, argon, krypton, and/or xenon gas mixed with the nitrogen. These gases can be used to inhibit the BNNT self assembly process during start up, thereby reducing impurities in the BNNT material. Once the boron melt **58** and **68** has reached the desired temperature, the amounts of as helium, neon, argon, krypton and/or xenon can be reduced and the BNNT self assembly can proceed.

After the boron feed stock is sufficiently heated to become adequately electrically conductive, the Direct Induction eddy currents in the boron feedstock heat the boron feedstock until it forms a boron melt **64**. The Lorentz forces from the Direct Induction coil(s) and/or concentrator (see FIGS. **3** and **4**) can be utilized to alter the shape of the boron melt **64** such that the top portion of the melt **62** is typically of smaller diameter than the bottom portion of the melt **63**. Multiple frequencies in the Direct Induction currents, spacing of the Direct Induction coils or concentrators (both coil-to-coil spacings and inner diameter spacings) can be manipulated to control both the shape of the boron melt **64** and the vertical heating profile of the boron melt **64**. The shape of the boron melt **64** is an important factor for several reasons. For example, the bottom region of the boron melt **63** must stay below the melting point of the mostly boron nitride crust **66** that forms on the bottom side of the boron melt **64**. Otherwise, the crust **66** will melt, and the boron melt **64** would then melt the boron nitride crucible **510**. Also, the top region of the boron melt **62** must reach the smoking point, such that the B/BN molecules evaporate from the top of the boron melt **64**. In addition, some of the nitrogen gas entering the chamber (not shown) dissolves into the boron melt and contributes to the formation of the B/BN molecules as the temperature of the boron melt increases. The rate of nitrogen dissolution is temperature dependent and increases with temperature. Having the ability to adjust the heat profile on the boron melt **64** can be used to vary the temperature distribution across the boron melt **64** and thereby vary the nitrogen dissolution and consequent evolution of B/BN.

The laser beams **67** and electric arc illustrated FIG. **6** can also be utilized to further control the heating and consequent temperature profile on the top region of the boron melt **62** as a way of controlling the local flux distribution of B/BN molecule production. Further, this heating distribution can contribute to the control of the shear forces and heat profile in the self-assembly region **61**. Controlling the BNNT self-assembly process is important for the quality of the BNNT material including the alignment of the BNNT fibers.

If molybdenum, tungsten, or other refractory metal are utilized, it should be understood that these metals are not catalysts in the BNNT synthesis process and further do not appear in the BNNTs. Instead, these metals only aid in the process to bring the boron feedstock to a level of electrical

conductivity where the feedstock can be heated by Direct Induction from the Direct Induction coils or concentrator.

FIG. **7** provides a basic process flowchart for the synthesis of high quality BNNT via Direct Induction. At step **S701**, the boron feedstock, such as solid boron or boron nitride, is placed in a crucible. In optional step **S702**, the boron feedstock may be doped with a refractory metal. Simply placing pieces of the refractory metal in the boron feed stock works; additionally, the boron feedstock can already be a mixture for example of boron, boron nitride and the refractory metal. At step **S703**, nitrogen gas flow is introduced to the chamber. The nitrogen gas flow may be at an elevated pressure, from about 1 atm to about 250 atm, and including, for example, from about 1 atm to about 12 atm. Additionally, noble gases such as helium, neon, argon, krypton and/or xenon may be present especially during start up while the boron melt is being achieved. After the desired operating pressure is achieved, at step **S704** the nitrogen flow circulation is initiated. At step **S705**, power is supplied to the Direct Induction coils. In embodiments including an additional heat source, such as a laser or electric arc, option step **706** involves focusing the laser(s) at the feedstock to form the boron melt and a boron nitride crust. After the boron melt is formed, the additional heat source may be removed, or adjusted as part of step **S707** to control the BNNT synthesis. At step **S707**, the coil power and any additional heat is manipulated to control the shape of the boron melt and heat profile in the chamber. During the step, the reaction of boron and nitrogen in and on the surface of the boron melt results in the evolution of B/BN in a downstream direction of the boron melt, in the direction of the nitrogen flow. BNNTs will self-assembly from the boron droplets and B/BN. At step **S708**, cooling of coils and nitrogen flow is performed to control the shear profiles in the chamber, and in particular downstream of the boron melt. The shear profiles in the chamber direct the self-assembled BNNTs downstream, and align the BNNTs into BNNT fibers. At step **S709**, which may be optional in some embodiments, the boron feedstock may be replenished through the addition of feedstock material. For example, rods of boron can be inserted from near the top edge of the crucible **510**, boron or boron nitride powder can simply be dropped in from above, or a tube furnace arrangement, not shown, may preheat particles of boron or boron nitride and allow them to fall onto the boron melt **64** from above the boron melt **64**.

It should be apparent from the present approach that Direct Induction may be used as a tool to efficiently provide heat to a boron feedstock and/or boron melt, its support, and BNNT self-assembly regions, and thereby drive the chemical reaction processes that are to some extent within the boron melt in terms of creating B/BN molecules, though the chemical processes (i.e., BNNT self-assembly) are downstream of the boron melt and external to the boron melt. It should be appreciated that the present approach calls for more than merely heating boron with Direct Induction, and involves a complex series of chemical reactions leading to BNNT self assembly driven by heat supplied in various stages and at various locations, either all or in part by Direct Induction.

Some embodiments may benefit from controlling the temperature of various components, so as to establish a generally steady-state operation. One of ordinary skill should recognize that the temperature profile during operation may have an impact on the BNNT self-assembly flux and shear forces on the forming BNNT molecules. Thus, downstream portions of the apparatus may be configured to

generate and maintain the desired sheering and velocity profiles to produce the desired BNNT products.

FIG. 8 is a photograph showing BNNTs synthesized using Direct Induction according to an embodiment of the present approach, and in particular a “cobweb” of BNNTs recovered above the boron melt 17 in a prototype apparatus similar to the embodiment shown in FIG. 4. The clear tube in the apparatus was approximately 3 cm in diameter and the BNNT “cobweb” was about 10 cm in length. As the demonstration using the prototype apparatus was of relatively short duration with a slow heating of about 10 minutes with BNNT cobweb forming in less than 10 seconds. There was no additional heat or cooling provided to self-assembly region. The demonstration did not require a laser for additional heating, as the Direct Induction coils provided adequate heat, but the boron feedstock included refractory metals to provide electrical conductivity needed for forming the boron melt.

FIG. 9 shows a transmission electron microscope (TEM) image of the BNNTs shown in FIG. 8. The BNNTs long fibers mostly running from the upper left to the lower right of the image, along with a collection of boron and boron nitride particles also formed in the process, against a structure of a lacy carbon grid in the form of an “X” used to support the BNNTs in the TEM. The BNNTs observed are few-wall and have lengths that typically span far beyond the approximately 2.5 microns width of the image. The operating conditions were appropriate for an initial proof of concept, but it should be appreciated that the prototype apparatus used was not configured for minimizing the amounts of the boron and boron nitride particles in the product, or collecting large quantities of BNNT material.

The mechanical structures, water cooling for the coils and surrounding surfaces, the nitrogen pressure chamber, and the systems to harvest the BNNTs, are not shown in the FIGS. 1, 2, 3, 5 and 6. As one of ordinary skill should appreciate, a diverse number of arrangements for the heat sources, cooling, and electromechanical arrangements can be combined to provide the efficient production of BNNTs in various forms. For example, see related applications U.S. Provisional Patent Application No. 62/164,997, U.S. Provisional Patent Application No. 62/194,972, and International Application No. PCT/US2015/58615, all of which are incorporated by reference in their entirety.

Production of high quality BNNTs can be achieved by utilizing Direct Induction technology as the heat source for driving the BNNT self-assembly process. Appropriate structures, materials, geometries, sizes and processes must be utilized. Conditions for achieving sustained production of BNNTs have been demonstrated.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the approach. As used herein, the singular forms “a,” “an,” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

The principles described herein may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The present embodiments are therefore to be considered in all respects as illustrative and not restrictive.

What is claimed is:

1. A process for synthesizing boron nitride nanotubes (BNNTs), the process comprising:
 - feeding gas containing nitrogen to a chamber in a first direction;
 - pre-heating a boron feedstock in the chamber to form an electrically conductive boron material;
 - supplying power to a Direct Induction coil surrounding the electrically conductive boron material;
 - heating the electrically conductive boron material through induction heating from the Direct Induction coil to form a boron melt;
 - wherein boron and boron-nitrogen evaporate from the boron melt in the first direction, and BNNTs self-assemble from the evaporated boron and boron-nitrogen downstream from the boron melt in the first direction.
2. The process of claim 1, wherein pre-heating the boron feedstock to form an electrically conductive boron material comprises heating the boron feedstock to a temperature above 800° C. and below the melting temperature of boron nitride.
3. The process of claim 1, wherein forming the boron melt causes a portion of the nitrogen in the gas entering the chamber to dissolve in the boron melt and evaporate boron nitride from the boron melt in the first direction.
4. The process of claim 1, wherein the boron feedstock includes a refractory metal.
5. The process of claim 1, wherein the boron feedstock is supported in a crucible in the chamber.
6. The process of claim 5, wherein the crucible is supported in a Direct Induction eddy current field concentrator.
7. The process of claim 5, wherein the crucible is supported by a Direct Induction coil.
8. The process of claim 5, further comprising cooling the crucible.
9. The process of claim 1, further comprising depositing a layer of boron nitride under the boron feedstock.
10. The process of claim 1, wherein BNNTs self-assemble and align in a growth zone downstream of the boron melt in the first direction.
11. The process of claim 1, wherein pre-heating the boron feedstock to form an electrically conductive boron material comprises heating the boron feedstock with at least one laser.
12. The process of claim 1, wherein pre-heating the boron feedstock to form an electrically conductive boron material comprises heating the boron feedstock with at least one electric arc.
13. The process of claim 1, further comprising feeding at least one noble gas to the chamber.
14. The process of claim 1, wherein BNNTs self-assemble in a growth zone downstream of the boron melt in the first direction, and further comprising supplying power to a second Direct Induction coil surrounding at least a portion of the growth zone.
15. The process of claim 1, wherein BNNTs self-assemble in a growth zone downstream of the boron melt in the first direction, and further comprising supplying power to a direct current coil surrounding at least a portion of the growth zone.
16. The process of claim 1, further comprising controlling the flow rate of the nitrogen gas at the boron melt and in a BNNT self-assembly growth zone downstream of the boron melt.
17. A process for synthesizing boron nitride nanotubes (BNNTs), the process comprising:

feeding gas containing nitrogen to a chamber in a first direction;
pre-heating a boron feedstock in the chamber to a temperature above 800° C. to form an electrically conductive boron material; 5
supplying power to a Direct Induction coil surrounding the electrically conductive boron material;
heating the electrically conductive boron material through induction heating from the Direct Induction coil to form a boron melt; 10
wherein BNNTs self-assemble from boron and boron-nitrogen evaporating downstream from the boron melt in the first direction.

18. The process of claim **1**, wherein the boron feedstock contains a layer of boron nitride. 15

19. The process of claim **17**, wherein the boron feedstock includes a refractory metal.

20. The process of claim **19**, wherein refractory material comprises at least one of molybdenum and tungsten. 20

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